Summary Report for Electroweak Symmetry Breaking Session in LCWS 2004

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Theoretical activities on the Higgs physics and its implication to physics beyond the standard model are summarized as the summary report for the Higgs session in LCWS 2004.

1 Introduction

The origin of electroweak symmetry breaking has been of a central interest in high energy physics for over two decades, and will continue being so in future until it will be clarified by the experiment. In the standard model (SM), the electroweak symmetry is spontaneously broken by introducing an iso-doublet scalar field, the Higgs field. Its neutral component receives the vacuum expectation value (v). The weak gauge bosons then obtain their masses through the Higgs mechanism. At the same time, all quarks and charged leptons receive the masses from the Yukawa interactions with the Higgs field. Moreover, the Higgs boson (h) itself is also given its mass (m_h) by the vacuum expectation value through the self-interaction of the Higgs boson. All these masses of the SM particles are expressed as multiplication of coupling constants with v. Therefore, there is an universality between masses and coupling constants:

$$\frac{2m_W}{g} = \frac{\sqrt{2}m_t}{y_t} = \frac{\sqrt{2}m_b}{y_b} = \frac{\sqrt{2}m_\tau}{y_\tau} = ... = \frac{m_h}{\sqrt{2\lambda}} = v \simeq 246\text{GeV}, \qquad (1)$$

where g is the weak gauge coupling, y_f is the Yukawa coupling constant to the fermion f, λ is the self-coupling constant of h, and m_i is the mass of the field i. The SM can be tested through this universality.

The Higgs boson h is yet to be discovered, and its mass m_h remains unknown. In the SM, m_h is a parameter which characterizes the property of the Higgs dynamics. Since $m_h \propto \sqrt{\lambda}v$, a light h means that the Higgs sector is weakly-interacted, while a heavy h corresponds to the strong coupling. Although m_h is an unknown parameter, by putting the requirement that the theory must be consistent up to a given value of the cutoff scale Λ, the allowed region of m_h can be predicted as a function of Λ [1]. Based on this requirement, a renormalization group equation analysis for the coupling constant λ gives upper and the lower bounds on m_h for a given Λ. In the SM, for $\Lambda = 10^{19}$ GeV, the allowed region of m_h is evaluated as about $135 < m_h < 180$ GeV

while for $\Lambda = 10^3$ GeV it is about $m_h < 480$ GeV. Hence, as long as the SM Higgs sector is assumed, a light Higgs boson would indicate a weakly coupled theory with a high cut-off scale. Scenarios based on grand unified theories (GUTs) might correspond to this case. In such cases, supersymmetry (SUSY) would necessarily be required to reduce the problem of large hierarchy between the weak scale and the scale of Λ. On the contrary, a heavy Higgs boson with $m_h \sim$ several hundred GeV would imply a strongly-coupled Higgs sector with a low $\Lambda \sim \mathcal{O}(1)$ TeV. In such a case, the Higgs sector should be considered as an effective theory of a new dynamics at TeV scales. Therefore, from knowing the mass of the Higgs boson, a useful hint for new physics beyond the SM can be obtained.

In addition to the mass of the Higgs boson, tri-linear couplings of hVV ($g_{hVV}g_{\mu\nu}$), where $VV = ZZ$ and W^+W^-, and hhh (λ_{hhh}) are particularly important to test the Higgs sector. These couplings are absent in the Lagrangian, and are induced according to electroweak symmetry breaking from the $hhVV$ and $hhhh$ interactions, respectively. In the SM, the hZZ and hhh couplings can be expressed in terms of m_Z and m_h as [2]:

$$g_{hZZ} = \frac{2m_Z^2}{v}\left(1 - \frac{5}{32\pi^2}\frac{m_t^2}{v^2} + ...\right), \quad \lambda_{hhh} = -\frac{3m_h^2}{v}\left(1 - \frac{1}{\pi^2}\frac{m_t^4}{v^2 m_h^2} + ...\right), \quad (2)$$

The first equation is useful to directly test the nature of the Higgs mechanism, while the second one can be used to explore the structure of Higgs sectors. Moreover, precise determination of the Yukawa coupling constants is essential to study the structure of the fermion mass generation.

Experimental identification of the Higgs boson is one of the most important goals of high energy collider experiments. The LEP Electroweak Working Group fit favors a relatively light Higgs boson with its mass below 251 GeV, assuming the SM [3]. The search for the Higgs bosons is being carried at Fermilab Tevatron and will be continued at CERN Large Hadron Collider (LHC). There, the SM Higgs boson is expected to be discovered as long as its mass is less than 1 TeV. An electron-positron linear collider (LC) and its photon collider option can provide good opportunity for precise measurement of the Higgs boson couplings. At a LC, the Higgs boson h is produced mainly via the Higgsstrahlung process $e^+e^- \to Zh$ for relatively low energies and also via the fusion process $e^+e^- \to W^{+*}W^{-*}\nu\bar{\nu} \to h\nu\bar{\nu}$ for higher energies [4]. In both production mechanisms, the Higgs boson is produced through the coupling with weak gauge bosons hVV. The cross sections are expected to be measured at a percent level or better unless the Higgs boson is relatively heavy. The Higgs boson couplings with heavy quarks (except the top quark) and the tau lepton can be tested by measuring the decay branching ratios of the

Higgs boson. Furthermore, the tri-linear Higgs coupling hhh [5,6,7] and the top-Yukawa coupling $ht\bar{t}$ can be determined by 10-20% accuracy by measuring the cross section of double Higgs production processes $e^+e^- \to Zhh$ as well as $e^+e^- \to W^{+*}W^{-*}\nu\bar{\nu} \to hh\nu\bar{\nu}$ and the top-associated Higgs production process [8] $e^+e^- \to ht\bar{t}$, respectively. The $\gamma\gamma$ option of the LC can also be useful for determination of the CP property and the couplings of the Higgs boson [9].

2 Extended Higgs sectors and new physics

Studying the Higgs sector is not only useful for the confirmation of the breaking mechanism of the electroweak gauge symmetry in the SM, but also provides a sensitive window for new physics beyond the SM. In many models of new physics, an extended Higgs sector from the SM one appears in the low energy effective theory, which has discriminative phenomenological properties. In extended Higgs sectors, there is mixing among more than one Higgs bosons, so that the relations in Eq. (2) are modified due to the mixing effect [10,11] as well as the loop effect of extra Higgs bosons [12,2]. If an extended Higgs sector such as the two Higgs doublet model (THDM) or some other extension of the SM Higgs sector is assumed, the theoretical bounds on the mass of the lightest Higgs boson are changed for a given cut-off scale [13,14].

One popular example for new physics models is the minimal supersymmetric standard model (MSSM), in which the Higgs sector is a THDM [15]. The most important prediction in the MSSM is that for the mass of the lightest Higgs boson [16]. The coupling constants in the Higgs potential are given by the electroweak gauge coupling constants which are originated from the D-term contribution. Thus, the mass of the lightest CP-even Higgs boson is limited at tree level to be less than the mass of the Z boson, and at loop levels the upper limit is shifted to be around 135 GeV by radiative corrections [17]. The predicted mass m_h of the Higgs boson is sensible to the SUSY parameters, so that both precise measurement of m_h and unambiguous theoretical prediction for m_h are quite important to obtain the detailed information of SUSY [16].

Some models based on dynamical breaking of the electroweak symmetry also require more than one Higgs doublets in the low energy effective theories [18]. In general such models induce relatively strong coupling constants in the effective Higgs potential, and the typical masses of the Higgs bosons are larger than the lightest Higgs boson in weakly coupled models. As discussed, the present experimental data [3] indicate a weakly interacting Higgs boson in the minimal Higgs sector. This experimental upper limit, however, strongly depends on the model. In extended Higgs models, there are additional contributions to the weak boson two-point functions which could cancel those of the

SM Higgs boson loop, so that the lightest Higgs boson heavier than 251 GeV can be allowed [19]. Hence, in order for strongly-coupled dynamical models to be consistent with the low energy data, an extended Higgs sector is required in the low energy effective theory.

There are other motivations to introduce extra Higgs fields at low energy, such as electroweak baryogenesis [20], neutrino mass problem [14], and top-bottom mass hierarchy [21].

A common feature of extended Higgs sectors is the existence of additional scalar bosons, such as charged Higgs bosons and CP-odd Higgs boson(s). Discovery of these extra scalar particles would directly show a new physics model beyond the SM. Once these additional Higgs bosons are found, we would be able to test each new physics model by measuring details of their properties. Various production processes of heavy neutral Higgs bosons and the charged Higgs boson at a LC are studied in the MSSM (THDM) [22]. A $\gamma\gamma$ collider provides further opportunity for the heavy Higgs search, where various properties of the heavy Higgs bosons, such as CP-property, can be explored [9,23,24,25].

Even if the extra Higgs bosons are not found, we can still obtain insight by looking for indirect effects of the extra Higgs boson from the precise determination of the lightest Higgs boson properties [26]. General features of such indirect effects can be learned through the study of decoupling property in the THDM [10]. The tree-level couplings with weak gauge bosons hVV ($VV = WW$ and ZZ) are changed by the factor of $\sin(\beta-\alpha)$, where α is the mixing angle of CP-even Higgs bosons and $\tan\beta$ is the ratio of the vacuum expectation values. The other couplings such as $hf\bar{f}$ (f: a fermion) and hhh are also changed. In the limit $\sin(\beta-\alpha) \to 1$, these couplings become the same as those in the SM. In addition to the mixing effect, the couplings can receive large quantum corrections provided that the extra Higgs bosons have the non-decoupling property. When their masses are predominantly generated by v, contributions in powers of the mass of the loop particles can appear in the one loop effect on the couplings of hZZ and hhh, similar to the top-quark loop effect seen in Eq. (2). They are quadratic for the hVV coupling and quartic for the hhh coupling [2,27]. Similar non-decoupling effects [28] can also appear in $h \to \gamma\gamma$ [29,30], $h \to b\bar{b}$ [30], $e^+e^- \to W^+W^-$ [31] and those with the coupling $W^\pm H^\mp Z$ [32]. These observables can receive significant corrections due to the non-decoupling effect even in the SM-like limit $\sin(\beta-\alpha) \to 1$. On the contrary, when the heavy Higgs bosons obtain the masses mainly from an invariant mass parameter, such power-like contribution disappears, and the loop effects vanish in the limit where the mass of additional Higgs bosons is large. The MSSM Higgs sector belongs to this case. A systematic approach to the correlation in the deviations among various observables is necessary for such cases [26].

3 Activities in Electroweak Symmetry Breaking Session

In the following, I summarize some of the theoretical contributions to the Higgs session in LCWS 2004. Those related to photon colliders and experimental topics are treated elsewhere [9,33].

The ability of precise measurement at a future LC can be useful for determination of coupling constants, only when ambiguity in theory prediction is sufficiently suppressed. In particular, the production cross sections and decay branching ratios of the Higgs boson have to be evaluated as precise as possible with including higher order contributions of perturbation especially in the bench mark theory such as the SM and the MSSM. In the SM, the results of complete electroweak $\mathcal{O}(\alpha)$ radiative corrections to the Higgs boson production cross sections $e^+e^- \to \nu_\ell \bar{\nu}_\ell h$ and $e^+e^- \to t\bar{t}h$ were presented by Dittmaier [34]. In the MSSM, the mass of the lightest Higgs boson m_h is an output quantity, which is sensible to the SUSY parameters. The precise determination of m_h at experiment is quite important to obtain the detailed information of SUSY. At a LC, the expected experimental error of the m_h measurement can be 50 MeV. Heinemeyer claimed that the intrinsic error in the theoretical prediction of m_h can be reduced to 0.5-0.1 GeV by a full two loop calculation with including the leading three loop leading contribution [16]. The one-loop corrected decay rates of the heavy neutral Higgs bosons into a pair of charginos and neutralinos are evaluated in the MSSM by Eberl [35].

In recent years, the MSSM with additional CP phases (CPVMSSM) has been studied intensively by many authors [36]. The phenomenology of the CPVMSSM is shown to be largely different from the CP conserving MSSM due to the effect of CP violating phases. Akeroyd discussed the case in which the typical SUSY breaking scale (M_{SUSY}) is as large as several TeV [37]. With such values of M_{SUSY}, the predictions on the EDM processes are suppressed below the current experimental upper limits. The phenomenology of CP violation in the non-SUSY THDM was also discussed [23,38,39].

The simplest extension of the MSSM is known as the next-to-MSSM [15]. Miller studied details of the phenomenology in a specific scenario in which the lightest SUSY particle (LSP) is the singlino, the super-partner of the additional singlet field [40]. The phenomenology of the next-to-MSSM with CP violating phases was also discussed by Gunion [41].

Baryogenesis is one of the fundamental cosmological problems. Electroweak baryogenesis [20] is a scenario of baryogenesis at the electroweak phase transition. The Higgs sector plays an essentially important role. For electroweak baryogenesis it is required that the phase transition is strongly first order. Okada discussed the phenomenological implication of a viable scenario

in the THDM [27]. It was shown that the condition for successful baryogenesis on the finite temperature effective potential exactly corresponds to the condition of large non-decoupling loop effect on the hhh coupling due to extra Higgs boson loops for the lightest Higgs boson. Such large non-decoupling effects deviates the hhh coupling by 10% or more [2], so that the scenario of electroweak baryogenesis can be tested by measuring the hhh coupling at a LC.

Extra dimensions could provide a candidate for new physics which removes the hierarchy problem. In models of large extra dimensions, there is an interaction between the Ricci scalar curvature and the Higgs doublet field. A phenomenological consequence can be an invisible decay of the Higgs boson to Kaluza Klein graviscalars. Dominici [42] discussed that the corresponding invisible width can cause a suppression of the LHC rates of a light Higgs in the visible channels below 5 σ for some case. In such a case the Higgs boson can be discovered through its invisible decay. The combination of the measurements at the LHC and the LC can determine the parameters of the model.

Lepton flavor violation (LFV) in charged leptons directly indicates new physics beyond the SM. In the models such as based on SUSY, in addition to the gauge boson mediated LFV process, the LFV Yukawa couplings are naturally induced by slepton mixing [43]. The direct search of such LFV Yukawa coupling would be possible by measuring the Higgs decay process of $h^0 \to \tau^\pm \mu^\mp$ at a LC. Ota discussed details of this possibility, and numerically showed the feasibility of this process from the Higgsstrahlung process at a LC, under the constraint from current data of LFV tau decay processes [44].

4 Conclusions

To explore the nature of electroweak symmetry breaking with its implication to new physics is top priority in high energy physics. The precision measurements of the Higgs sector are attained at a LC and its photon collider option, at which details of the model can be studied. In order to compare theoretical predictions with precision data at a LC, highly precise calculations for the Higgs boson observables are needed in the bench mark theories such as the SM and the MSSM. In addition, there are many new physics models beyond the SM or the MSSM, which would induce various discriminative extended Higgs sectors in the low energy effective theory. Phenomenological features of these extended Higgs sectors should be more studied to explore new physics. There remain many things for theorists to do for the Higgs physics at a LC.

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